Climate forcing growth rates: doubling down on our Faustian bargain

OPEN ACCESS
IOP PUBLISHING
ENVIRONMENTAL RESEARCH LETTERS
Environ. Res. Lett. **8** (2013) 011006 (9pp)
doi:10.1088/1748-9326/8/1/011006

PERSPECTIVE

Climate forcing growth rates: doubling down on our Faustian bargain

James Hansen, Pushker Kharecha and Makiko Sato
Goddard Institute for Space Studies and Columbia Earth Institute, 2880 Broadway, New York, NY 10025, USA
james.e.hansen@nasa.gov

Rahmstorf *et al*'s (2012) conclusion that observed climate change is comparable to projections, and in some cases exceeds projections, allows further inferences if we can quantify changing climate forcings and compare those with projections. The largest climate forcing is caused by well-mixed long-lived greenhouse gases. Here we illustrate trends of these gases and their climate forcings, and we discuss implications. We focus on quantities that are accurately measured, and we include comparison with fixed scenarios, which helps reduce common misimpressions about how climate forcings are changing.

Annual fossil fuel CO_2 emissions have shot up in the past decade at about 3% yr^{-1}, double the rate of the prior three decades (figure 1). The growth rate falls above the range of the IPCC (2001) 'Marker' scenarios, although emissions are still within the entire range considered by the IPCC SRES (2000). The surge in emissions is due to increased coal use (blue curve in figure 1), which now accounts for more than 40% of fossil fuel CO_2 emissions.

The resulting annual increase of atmospheric CO_2 (12-month running mean) has grown from less than 1 ppm yr^{-1} in the early 1960s to an average $\sim$2 ppm yr^{-1} in the past decade (figure 2). Although CO_2 measurements were not made at sufficient locations prior to the early 1980s to calculate the global mean change, the close match of global and Mauna Loa data for later years suggests that Mauna Loa data provide a good approximation of global change (figure 2), thus allowing a useful estimate of annual global change beginning with the initiation of Mauna Loa measurements in 1958 by Keeling *et al* (1973).

Interannual variability of CO_2 growth is correlated with ENSO (El Nino Southern Oscillation) variations of tropical temperatures (figure 2). Ocean–atmosphere CO_2 exchange is affected by ENSO (Chavez *et al* 1999), but ENSO seems to have a greater impact on atmospheric CO_2 via the terrestrial carbon cycle through effects on the water cycle, temperature, and fire, as discussed in a large body of literature (referenced, e.g., by Schwalm *et al* 2011). In addition, volcanoes, such as the 1991 Mount Pinatubo eruption, slow the increase of atmospheric CO_2 (Rothenberg *et al* 2012), at least in part because photosynthesis is enhanced by the increased proportion of diffuse sunlight (Gu *et al* 2003, Mercado *et al* 2009). Watson (1997) suggests that volcanic dust deposited on the ocean surface may also contribute to CO_2 uptake by increasing ocean productivity.

An important question is whether ocean and terrestrial carbon sinks will tend to saturate as human-made CO_2 emissions continue. Piao *et al* (2008) and Zhao and Running (2010) suggest that there already may be a reduction of terrestrial carbon uptake, while Le Quéré *et al* (2007) and Schuster and Watson (2007) find evidence of decreased carbon uptake in the Southern Ocean and North Atlantic Ocean, respectively. However, others (Knorr 2009, Sarmiento *et al* 2010,

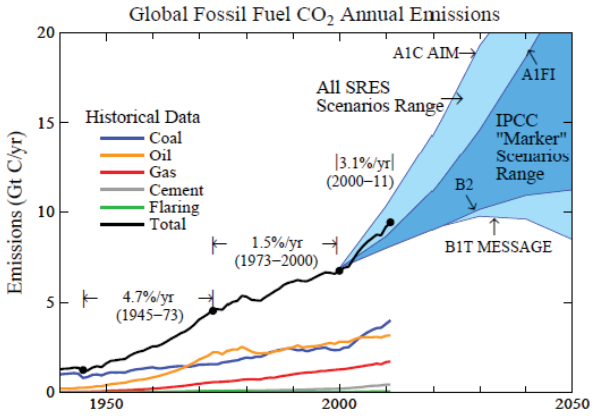

Figure 1. CO_2 annual emissions from fossil fuel use and cement manufacture, an update of figure 16 of Hansen (2003) using data of British Petroleum (BP 2012) concatenated with data of Boden *et al* (2012).

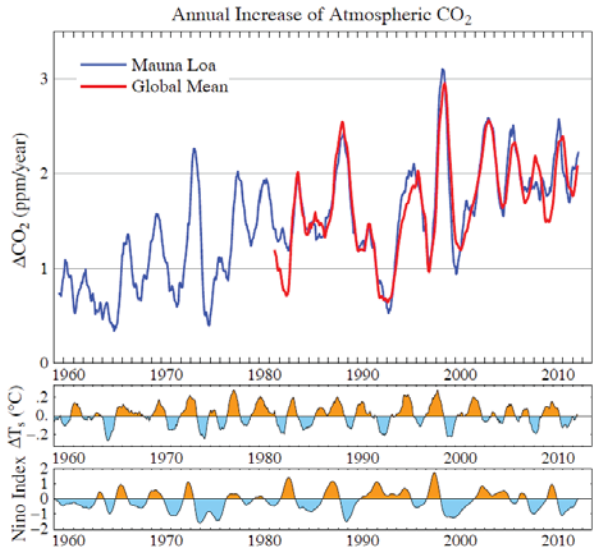

Figure 2. Annual increase of CO_2 based on data from the NOAA Earth System Research Laboratory (ESRL 2012). CO_2 change and global temperature change are 12-month running means of differences for the same month of consecutive years. Nino index (Nino3.4 area) is 12-month running mean. Both temperature indices use data from Hansen *et al* (2010). Annual mean CO_2 amount in 1958 was 315 ppm (Mauna Loa) and in 2012 was 394 ppm (Mauna Loa) and 393 ppm (Global).

Ballantyne *et al* 2012) either cast doubt on the reality of a reduced uptake strength or find evidence for increased uptake.

An informative presentation of CO_2 observations is the ratio of annual CO_2 increase in the air divided by annual fossil fuel CO_2 emissions (Keeling *et al* 1973), the 'airborne fraction' (figure 3, right scale). An alternative definition of airborne fraction includes in the denominator of this ratio an estimated net anthropogenic CO_2 source from changes in land use, but this latter term is much more uncertain than the two terms involved in the Keeling *et al* (1973) definition. For example, analysis by Harris *et al* (2012) reveals a range as high as a factor of 2–4 in estimates of recent land use emissions; see also the discussion by Sarmiento *et al* (2010). However, note that the airborne fraction becomes smaller when estimated land use emissions are included, with the uptake fraction (one minus airborne fraction) typically greater than 0.5.

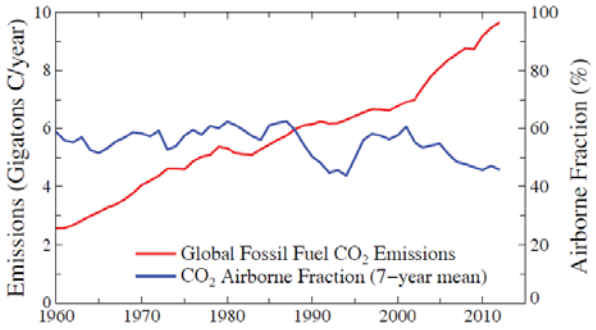

Figure 3. Fossil fuel CO_2 emissions (left scale) and airborne fraction, i.e., the ratio of observed atmospheric CO_2 increase to fossil fuel CO_2 emissions. Final three points are 5-, 3- and 1-year means.

The simple Keeling airborne fraction, clearly, is not increasing (figure 3). Thus the net ocean plus terrestrial sink for carbon emissions has increased by a factor of 3–4 since 1958, accommodating the emissions increase by that factor.

Remarkably, and we will argue importantly, the airborne fraction has declined since 2000 (figure 3) during a period without any large volcanic eruptions. The 7-year running mean of the airborne fraction had remained close to 60% up to 2000, except for the period affected by Pinatubo. The airborne fraction is affected by factors other than the efficiency of carbon sinks, most notably by changes in the rate of fossil fuel emissions (Gloor *et al* 2010). However, it is the dependence of the airborne fraction on fossil fuel emission rate that makes the post-2000 downturn of the airborne fraction particularly striking. The change of emission rate in 2000 from 1.5% yr^{-1} to 3.1% yr^{-1} (figure 1), other things being equal, would have caused a sharp increase of the airborne fraction (the simple reason being that a rapid source increase provides less time for carbon to be moved downward out of the ocean's upper layers).

A decrease in land use emissions during the past decade (Harris *et al* 2012) could contribute to the decreasing airborne fraction in figure 3, although Malhi (2010) presents evidence that tropical forest deforestation and regrowth are approximately in balance, within uncertainties. Land use change can be only a partial explanation for the decrease of the airborne fraction; something more than land use change seems to be occurring.

We suggest that the huge post-2000 increase of uptake by the carbon sinks implied by figure 3 is related to the simultaneous sharp increase in coal use (figure 1). Increased coal use occurred primarily in China and India (Boden *et al* 2012; BP 2012; see graphs at www.columbia.edu/∼mhs119/Emissions/Emis_moreFigs/). Satellite radiance measurements for July–December, months when desert dust does not dominate aerosol amount, yield an increase of aerosol optical depth in East Asia of about 4% yr^{-1} during 2000–2006 (van Donkelaar *et al* 2008). Associated gaseous and particulate emissions increased rapidly after 2000 in China and India (Lu *et al* 2011, Tian *et al* 2010). Some decrease of the sulfur component of emissions occurred in China after 2006 as wide application of flue-gas desulfurization began to be initiated (Lu *et al* 2010), but this was largely offset by continuing emission increases from India (Lu *et al* 2011).

We suggest that the surge of fossil fuel use, mainly coal, since 2000 is a basic cause of the large increase of carbon uptake by the combined terrestrial and ocean carbon sinks. One mechanism by which fossil fuel emissions increase carbon uptake is by fertilizing the biosphere via provision of nutrients essential for tissue building, especially nitrogen, which plays a critical role in controlling net primary productivity and is limited in many ecosystems (Gruber and Galloway 2008). Modeling (e.g., Thornton *et al* 2009) and field studies (Magnani *et al* 2007)

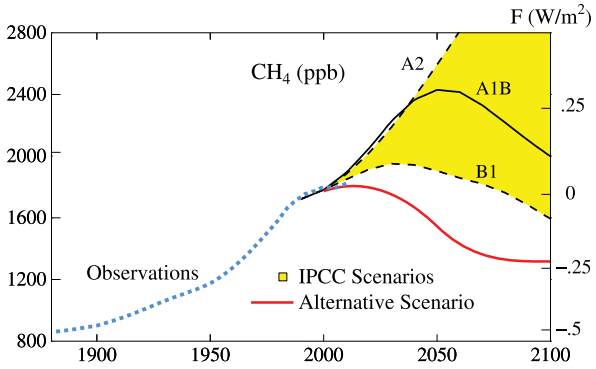

Figure 4. Observed atmospheric CH_4 amount and scenarios for twenty first century. Alternative scenario (Hansen *et al* 2000, Hansen and Sato 2004) yields maximum global warming ~1.5 °C above 1880–1920. Other scenarios are from IPCC (2001). Forcing on right hand scale is adjusted forcing, Fa, relative to values in 2000 (Hansen *et al* 2007).

confirm a major role of nitrogen deposition, working in concert with CO_2 fertilization, in causing a large increase in net primary productivity of temperate and boreal forests. Sulfate aerosols from coal burning also might increase carbon uptake by increasing the proportion of diffuse insolation, as noted above for Pinatubo aerosols, even though the total solar radiation reaching the surface is reduced.

Thus we see the decreased CO_2 airborne fraction since 2000 as sharing some of the same causes as the decreased airborne fraction after the Pinatubo eruption (figure 3). CO_2 fertilization is likely the major effect, as a plausible addition of 5 TgN yr^{-1} from fossil fuels and net ecosystem productivity of 200 kgC kgN^{-1} (Magnani *et al* 2007, 2008) yields an annual carbon drawdown of 1 GtC yr^{-1}, which is of the order of what is needed to explain the post-2000 anomaly in airborne CO_2. However, an aerosol-induced increase of diffuse radiation might also contribute. Although tropospheric aerosol properties are not accurately monitored, there are suggestions of an upward trend of stratospheric background aerosols since 2000 (Hofmann *et al* 2009, Solomon *et al* 2011), which could be a consequence of more tropospheric aerosols at low latitudes where injection of tropospheric air into the stratosphere occurs (Holton *et al* 1995). We discuss climate implications of the reduced CO_2 airborne fraction after presenting data for other greenhouse gases.

Atmospheric CH_4 is increasing more slowly than in IPCC scenarios (figure 4), which were defined more than a decade ago (IPCC 2001). However, after remaining nearly constant for several years, CH_4 has increased during the past five years, pushing slightly above the level that was envisaged in the Alternative Scenario of Hansen *et al* (2000). Reduction of CH_4, besides slowdown in CO_2 growth in the twenty first century and a decline of CO_2 in the twenty second century, is a principal requirement to achieve a low climate forcing that stabilizes climate, in part because CH_4 also affects tropospheric ozone and stratospheric water vapor. The Alternative Scenario, defined in detail by Hansen and Sato (2004), keeps maximum global warming at ~1.5 °C relative to 1880–1920, under the assumption that fast-feedback climate sensitivity is ~3 °C for doubled CO_2 (Hansen *et al* 2007). The Alternative Scenario allows CO_2 to reach 475 ppm in 2100 before declining slowly; this scenario assumes that reductions of non-CO_2 greenhouse gases and black carbon aerosols can be achieved sufficient to balance the warming effect of likely future decreases of reflective aerosols.

There are anthropogenic sources of CH_4 that potentially could be reduced, indeed, the leveling off of CH_4 amount during the past 20 years seems to have

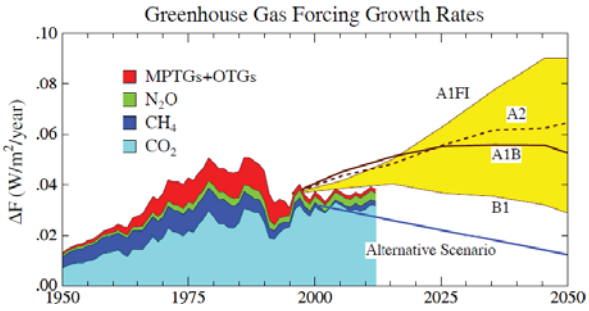

Figure 5. Five-year mean of the growth rate of climate forcing by well-mixed greenhouse gases, an update of figure 4 of Hansen and Sato (2004). Forcing calculations use equations of Hansen *et al* (2000). The moderate uncertainties in radiative calculations affect the scenarios and actual greenhouse gas results equally and thus do not alter the conclusion that the actual forcing falls below that of the IPCC scenarios.

been caused by decreased venting in oil fields (Simpson *et al* 2012), but the feasibility of overall CH_4 reduction also depends on limiting global warming itself, because of the potential for amplifying climate-CH_4 feedbacks (Archer *et al* 2009, Koven *et al* 2011). Furthermore, reduction of atmospheric CH_4 might become problematic if unconventional mining of gas, such as 'hydro-fracking', expands widely (Cipolla 2009), as discussed further below.

The growth rate for the total climate forcing by well-mixed greenhouse gases has remained below the peak values reached in the 1970s and early 1980s, has been relatively stable for about 20 years, and is falling below IPCC (2001) scenarios (figure 5). However, the greenhouse gas forcing is growing faster than in the Alternative Scenario. MPTGs and OTGs in figure 5 are Montreal Protocol Trace Gases and Other Trace Gases (Hansen and Sato 2004).

If greenhouse gases were the only climate forcing, we would be tempted to infer from Rahmstorf's conclusion (that actual climate change has exceeded IPCC projections) and our conclusion (that actual greenhouse gas forcings are slightly smaller than IPCC scenarios) that actual climate sensitivity is on the high side of what has generally been assumed. Although that may be a valid inference, the evidence is weakened by the fact that other climate forcings are not negligible in comparison to the greenhouse gases and must be accounted for.

Natural forcings, by changing solar irradiance and volcanic aerosols, are well-measured since the late 1970s and included in most IPCC (2007) climate simulations. The difficulty is human-made aerosols. Aerosols are readily detected in satellite observations, but determination of their climate forcing requires accurate knowledge of changes in aerosol amount, size distribution, absorption and vertical distribution on a global basis—as well as simultaneous data on changes in cloud properties to allow inference of the indirect aerosol forcing via induced cloud changes. Unfortunately, the first satellite mission capable of measuring the needed aerosol characteristics (Aerosol Polarimetry Sensor on the Glory satellite, (Mishchenko *et al* 2007)) suffered a launch failure and as yet there are no concrete plans for a replacement mission.

The human-made aerosol climate forcing thus remains uncertain. IPCC (2007) concludes that aerosols are a negative (cooling) forcing, probably between -0.5 and -2.5 W m^{-2}. Hansen *et al* (2011), based mainly on analysis of Earth's energy imbalance, derive an aerosol forcing -1.6 ± 0.3 W m^{-2}, consistent with an analysis of Murphy *et al* (2009) that suggests an aerosol forcing about -1.5 W m^{-2} (see discussion in Hansen *et al* (2011)). This large negative aerosol forcing reduces the net climate forcing of the past century by about half (IPCC 2007; figure 1 of Hansen *et al* 2011). Coincidentally, this leaves net climate forcing comparable to the CO_2 forcing alone.

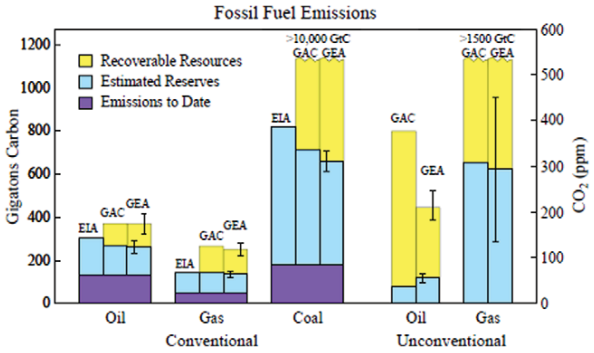

Figure 6. Fossil fuel CO_2 emissions and carbon content (1 ppm atmospheric CO_2 ~2.12 GtC). Historical emissions are from Boden *et al* (2012). Estimated reserves and potentially recoverable resources are based on energy content values of Energy Information Administration (EIA 2011), German Advisory Council (GAC 2011), and Global Energy Assessment (GEA 2012). We convert energy content to carbon content using emission factors of Table 4.2 of IPCC (2007) for coal, gas, and conventional oil, and, following IPCC, we use an emission factor of unconventional oil the same as that for coal.

Reduction of the net human-made climate forcing by aerosols has been described as a 'Faustian bargain' (Hansen and Lacis 1990, Hansen 2009), because the aerosols constitute deleterious particulate air pollution. Reduction of the net climate forcing by half will continue only if we allow air pollution to build up to greater and greater amounts. More likely, humanity will demand and achieve a reduction of particulate air pollution, whereupon, because the CO_2 from fossil fuel burning remains in the surface climate system for millennia, the 'devil's payment' will be extracted from humanity via increased global warming.

So is the new data we present here good news or bad news, and how does it alter the 'Faustian bargain'? At first glance there seems to be some good news. First, if our interpretation of the data is correct, the surge of fossil fuel emissions, especially from coal burning, along with the increasing atmospheric CO_2 level is 'fertilizing' the biosphere, and thus limiting the growth of atmospheric CO_2. Also, despite the absence of accurate global aerosol measurements, it seems that the aerosol cooling effect is probably increasing based on evidence of aerosol increases in the Far East and increasing 'background' stratospheric aerosols.

Both effects work to limit global warming and thus help explain why the rate of global warming seems to be less this decade than it has been during the prior quarter century. This data interpretation also helps explain why multiple warnings that some carbon sinks are 'drying up' and could even become carbon sources, e.g., boreal forests infested by pine bark beetles (Kurz *et al* 2008) and the Amazon rain forest suffering from drought (Lewis *et al* 2011), have not produced an obvious impact on atmospheric CO_2.

However, increased CO_2 uptake does not necessarily mean that the biosphere is healthier or that the increased carbon uptake will continue indefinitely (Matson *et al* 2002, Galloway *et al* 2002, Heimann and Reichstein 2008, Gruber and Galloway 2008). Nor does it change the basic facts about the potential magnitude of the fossil fuel carbon source (figure 6) and the long lifetime of the CO_2 in the surface carbon reservoirs (atmosphere, ocean, soil, biosphere) once the fossil fuels are burned (Archer 2005). Fertilization of the biosphere affects the distribution of the fossil fuel carbon among these reservoirs, at least on the short run, but it does not alter the fact that the fossil carbon will remain in these reservoirs for millennia.

Humanity, so far, has burned only a small portion (purple area in figure 6) of total fossil fuel reserves and resources. Yet deleterious effects of warming are apparent (IPCC 2007), even though only about half of the warming due to gases

now in the air has appeared, the remainder still 'in the pipeline' due to the inertia of the climate system (Hansen *et al* 2011). Already it seems difficult to avoid passing the 'guardrail' of no more than 2 °C global warming that was agreed in the Copenhagen Accord of the United Nations Framework Convention on Climate Change (UNFCCC 2010). And Hansen *et al* (2008), based primarily on paleoclimate data and evidence of deleterious climate impacts already at 385 ppm CO_2, concluded that an appropriate initial target for CO_2 was 350 ppm, which implied a global temperature limit, relative to 1880–1920 of about 1 °C. What is clear is that most of the remaining fossil fuels must be left in the ground if we are to avoid dangerous human-made interference with climate.

The principal implication of our present analysis probably relates to the Faustian bargain. Increased short-term masking of greenhouse gas warming by fossil fuel particulate and nitrogen pollution represents a 'doubling down' of the Faustian bargain, an increase in the stakes. The more we allow the Faustian debt to build, the more unmanageable the eventual consequences will be. Yet globally there are plans to build more than 1000 coal-fired power plants (Yang and Cui 2012) and plans to develop some of the dirtiest oil sources on the planet (EIA 2011). These plans should be vigorously resisted. We are already in a deep hole—it is time to stop digging.

Acknowledgments

We thank ClimateWorks, Energy Foundation, Gerry Lenfest (Lenfest Foundation), Lee Wasserman (Rockefeller Family Foundation), and Stephen Toben (Flora Family Foundation) for research and communications support.

References

Archer D 2005 Fate of fossil fuel CO_2 in geologic time *J. Geophys. Res.* **110** C09505

Archer D, Buffett B and Brovkin V 2009 Ocean methane hydrates as a slow tipping point in the global carbon cycle *Proc. Natl Acad. Sci.* **106** 20596–601

Ballantyne A P, Alden C B, Miller J B, Tans P P and White J W C 2012 Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years *Nature* **488** 70–2

Boden T A, Marland G and Andres R J 2012 *Global, Regional, and National Fossil-Fuel CO_2 Emissions* (Oak Ridge, TN: Carbon Dioxide Information and Analysis Center, Oak Ridge National Laboratory, US Department of Energy) doi:10.3334/CDIAC/00001_V2012

BP (British Petroleum) 2012 *Statistical Review of World Energy 2012* (www.bp.com/sectionbodycopy.do?categoryId=7500&contentId=7068481)

Chavez F P *et al* 1999 Biological and chemical response of the Equatorial Pacific Ocean to the 1997–1998 El Nino *Science* **286** 2126–31

Cipolla C L 2009 Modeling production and evaluating fracture performance in unconventional gas reservoirs *J. Petrol. Technol.* **61** 84–90

Earth System Research Laboratory (ESRL) 2012 *Trends in Atmospheric Carbon Dioxide* (www.esrl.noaa.gov/gmd/ccgg/trends/)

Energy Information Administration (EIA) 2011 *International Energy Outlook* (www.eia.gov/forecasts/ieo/pdf/0484(2011).pdf, accessed Sep. 2011)

Galloway J N, Cowling E B, Seitzinger S P and Socowlow R H 2002 Reactive nitrogen: too much of a good thing? *AMBIO* **31** 60–3

German Advisory Council on Global Change (GAC) 2011 *World in Transition—A Social Contract for Sustainability* (www.wbgu.de/en/flagship-reports/fr-2011-a-social-contract/, accessed Oct. 2011)

Global Energy Assessment (GEA) 2012 *Toward a Sustainable Future* ed T B Johanson *et al* (Luxemburg: International Institute for Applied Systems Analysis) p 118

Gloor M, Sarmiento J L and Gruber N 2010 What can be learned about carbon cycle climate feedbacks from the CO_2 airborne fraction? *Atmos. Chem. Phys.* **10** 7739–51

Gruber N and Galloway J N 2008 An Earth-system perspective of the global nitrogen cycle *Nature* **451** 293–6

Gu L *et al* 2003 Response of a deciduous forest to the Mount Pinatubo eruption: enhanced photosynthesis *Science* **299** 2035–8

Hansen J 2003 Can we defuse the global warming time bomb? *Natural Science* posted 1 Aug 2003

Hansen J 2009 *Storms of My Grandchildren: The Truth About the Coming Climate Catastrophe and Our Last Chance to Save Humanity* (New York: Bloomsbury) p 304

Hansen J E and Lacis A A 1990 Sun and dust versus greenhouse gases: an assessment of their relative roles in global climate change *Nature* **346** 713–9
Hansen J, Ruedy R, Sato M and Lo K 2010 Global surface temperature change *Rev. Geophys.* **48** RG4004
Hansen J and Sato M 2004 Greenhouse gas growth rates *Proc. Natl Acad. Sci.* **101** 16109–14
Hansen J, Sato M, Kharecha P and von Schuckmann K 2011 Earth's energy imbalance and implications *Atmos. Chem. Phys.* **11** 13421–49
Hansen J, Sato M, Ruedy R, Lacis A and Oinas V 2000 Global warming in the twenty-first century: an alternative scenario *Proc. Natl Acad. Sci.* **97** 9875–80
Hansen J *et al* 2007 Dangerous human-made interference with climate: a GISS modelE study *Atmos. Chem. Phys.* **7** 2287–312
Hansen J *et al* 2008 Target atmospheric CO_2: where should humanity aim? *Open Atmos. Sci.* **2** 217–31
Harris N L *et al* 2012 Baseline map of carbon emissions from deforestation in tropical regions *Science* **336** 1573–6
Heimann M and Reichstein M 2008 Terrestrial ecosystem carbon dynamics and climate feedbacks *Nature* **451** 289–92
Hofmann D, Barnes J, O'Niel M, Trudeau M and Neely R 2009 Increase in background stratospheric aerosol observed with lidar at Mauna Loa Observatory and Boulder, Colorado *Geophys. Res. Lett.* **36** L15808
Holton J R *et al* 1995 Stratosphere–troposphere exchange *Rev. Geophys.* **33** 403–39
IPCC (Intergovernmental Panel on Climate Change) 2000 *Special Report on Emission Scenarios (SRES)* ed N Nakicenovic *et al* (Cambridge: Cambridge University Press) p 599
IPCC (Intergovernmental Panel on Climate Change) 2001 *Climate Change 2001: The Scientific Basis* ed J T Houghton *et al* (Cambridge: Cambridge University Press) p 881
IPCC (Intergovernmental Panel on Climate Change) 2007 *Climate Change 2007: The Physical Science Basis* ed S Solomon *et al* (Cambridge: Cambridge University Press) p 996
Keeling C D, Whorf T P, Wahlen M and van der Plicht J 1973 Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980 *Nature* **375** 666–70
Knorr W 2009 Is the airborne fraction of anthropogenic CO_2 emissions increasing? *Geophys. Res. Lett.* **36** L21710
Koven C D *et al* 2011 Permafrost carbon-climate feedbacks accelerte global warming *Proc. Natl Acad. Sci.* **108** 14769–74
Kurz W A *et al* 2008 Mountain pine beetle and forest carbon feedback to climate change *Nature* **452** 987–90
Le Quéré C *et al* 2007 Saturation of the Southern Ocean CO_2 sink due to recent climate change *Science* **316** 1735–8
Lewis S L, Brando P M, Phillips O L, van der Heijden G M F and Nepstad D 2011 The 2010 Amazon drought *Science* **331** 554
Lu Z, Zhang Q and Streets D G 2011 Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996–2010 *Atmos. Chem. Phys.* **11** 9839–64
Lu Z *et al* 2010 Sulfur dioxide emissions in China and sulfur trends in East Asia since 2000 *Atmos. Chem Phys.* **10** 6311–31
Magnani F *et al* 2007 The human footprint in the carbon cycle of temperate and boreal forests *Nature* **447** 848–50
Magnani F *et al* 2008 Magnani et al. reply *Nature* **451** E28–9
Malhi Y 2010 The carbon balance of tropical forest regions, 1990–2005 *Curr. Opin. Environ. Sustain.* **2** 237–44
Matson P, Lohse K A and Hall S J 2002 The globalization of nitrogen deposition: consequences for terrestrial ecosystems *AMBIO* **31** 113–9
Mercado L M *et al* 2009 Impact of changes in diffuse radiation on the global land carbon sink *Nature* **458** 1014–7
Mishchenko M I *et al* 2007 Accurate monitoring of terrestrial aerosols and total solar irradiance: introducing the Glory mission *Bull. Am. Meteorol. Soc.* **88** 677–91
Murphy D M *et al* 2009 An observationally based energy balance for the Earth since 1950 *J. Geophys. Res.* **114** D17107
Piao S *et al* 2008 Net carbon dioxide losses of northern ecosystems in response to autumn warming *Nature* **451** 49–52
Rahmstorf S, Foster G and Cazenave A 2012 Comparing climate projections to observations up to 2011 *Environ. Res. Lett.* **7** 044035
Rothenberg D *et al* 2012 Volcano impacts on climate and biogeochemistry in a coupled carbon-climate model *Earth Syst. Dyn. Discuss.* **3** 279–323
Sarmiento J L *et al* 2010 Trends and regional distributions of land and ocean carbon sinks *Biogeosciences* **7** 2351–67
Schuster U and Watson A J 2007 A variable and decreasing sink for atmospheric CO_2 in the North Atlantic *J. Geophys. Res.* **112** C11006
Schwalm C R *et al* 2011 Does terrestrial drought explain global CO_2 flux anomalies induced by El Nino? *Biogeosciences* **8** 2493–506

Simpson I J *et al* 2012 Long-term decline of global atmospheric ethane concentrations and implications for methane *Nature* **488** 490–4
Solomon S *et al* 2011 The persistently variable 'background' stratospheric aerosol layer and global climate change *Science* **333** 866–70
Thornton P E *et al* 2009 Carbon–nitrogen interactions regulate climate-carbon cycle feedbacks: results from an atmosphere-ocean general circulation model *Biogeosciences* **6** 2099–120
Tian H Z *et al* 2010 Trend and characteristics of atmospheric emissions of Hg, As, and Se from coal combustion in China, 1980–2007 *Atmos. Chem. Phys.* **10** 11905–19
UNFCCC (United Nations Framework Convention on Climate Change) 2010 *Copenhagen Accord* (http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf, accessed 25 Nov. 2012)
van Donkelaar A *et al* 2008 Analysis of aircraft and satellite measurements from Interconinental Chemical Transport Experiment (INTEX-B) to quantify long-range transport of East Asian sulfur to Canada *Atmos. Chem. Phys.* **8** 2999–3014
Watson A J 1997 Volcanic iron, CO_2, ocean productivity and climate *Nature* **385** 587–8
Yang A and Cui Y 2012 Global coal risk assessment: data analysis and market research *WRI Working Paper* (Washington, DC: World Resources Institute) (www.wri.org/publication/global-coal-risk-assessment)
Zhao M and Running S W 2010 Drought-induced reduction in global terrestrial net primary production from 2000 through 2009 *Science* **329** 940–3